Introduction: Some historical "milestones" in the Leeuwin Current, and the Leeuwin Current Symposium 2007

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With this second Symposium focussing on the Leeuwin Current and its influence on the oceanography and marine biology off Western Australia, it is enlightening to look back at some of the key events/papers from the earliest speculations about the current system off our coast. It is only 3 decades since George Cresswell "discovered" and formally named the Leeuwin Current, yet in the relatively short time since then its unusual (and in many ways unique) characteristics have invoked ongoing local and international interest.

This brief introductory review traces some of the "milestones" which (in the author's opinion) have spelt out significant advances in our understanding of the structure, behaviour and significance of the Leeuwin Current system. As such, it provides an update to the historical review by Cresswell (1991) in the Proceedings of the first Leeuwin Current Symposium held in 1991.

Biological pioneers: Saville-Kent (1897) and others

Although early current charts showed a northwards boundary current off Western Australia, the fisheries biologist William Saville-Kent (1897) realised that there must in fact be a warm southerly flow to explain his observations of tropical marine species at the Abrolhos Islands and the large difference in (winter) temperature between the waters around the Islands and those at the adjacent mainland coast. Subsequent studies of the distribution of marine fauna and flora along the coast (*e.g.*, Michaelsen 1908; Dakin 1919) both confirmed and extended Saville-Kent's conjectures.

Rafts of warm surface water: Gentilli (1972)

An analysis of Indian Ocean sea-surface temperature charts by the geographer Joseph Gentilli (1972) revealed that there was a progression in the timing of the warmest water down the Western Australian coast. The warmest month on the Northwest Shelf was January, with the warm water progressively spreading southwards by April over a large area in the eastern Indian Ocean southward to (but offshore of) Shark Bay, with an isolated patch off Cape Leeuwin also in April. He attributed the presence and movement of these "rafts" to an inflow from the western Pacific Ocean, and sketched the southward movement of warm water down the Western Australian coastline.

New technologies and the naming of the Leeuwin Current: Cresswell & Golding (1980)

A major study of the larval stages of the western rock lobster during the mid-1970s coincided with the development of new oceanographic technologies. Self-recording current meters were deployed for periods of days to weeks at a number of sites on the outer continental shelf between the Abrolhos Islands and Rottnest Island (Cresswell *et al.* 1989) – these were the first *in situ* current meter measurements off south-Western Australia and indicated a seasonal change in the alongshore current direction. Satellite-tracked free-drifting buoys were also being developed at this time (Cresswell 1978), and the trajectories of a number of buoys released off the Western Australian continental shelf (Cresswell 1980) clearly revealed the complexity of the eddying southward stream and its easterly extension from Cape Leeuwin into the Great Australian Bight. Also at this time, satellite oceanography was just emerging as an operational reality, and early sea-surface temperature (SST) images of Western Australian waters showed the band of warm water and the associated eddy field (Legeckis & Cresswell 1981).

With this now conclusive evidence of the existence and nature of the southward flow, Cresswell & Golding (1980) formally named the Leeuwin Current.

Large-scale forcing of the Leeuwin Current: 1984–85

Following Thompson's (1984) suggestion that the southward flow (against the prevailing, and upwelling-favourable, wind system) could be caused by an anomalously strong alongshore pressure gradient, Godfrey & Ridgway (1985) used steric height and wind data to show the seasonal balance of forcing along the shelf break. They attributed seasonal changes in the meridional sea level gradient off Western Australia to the flow of Pacific Ocean water into the equatorial Indian Ocean through the chain of Indonesian islands.

The Leeuwin Current Interdisciplinary Experiment (LUCIE): 1986–87

Originally conceived as a multi-disciplinary survey of the Leeuwin Current, LUCIE evolved into a detailed oceanographic study of the current system in 1986/87, comprising research cruises complemented by current moorings along and across the continental shelf and slope (Boland *et al.* 1988). These were the first year-long direct current and hydrographic measurements across the Leeuwin Current, confirming the presence of the large alongshore geopotential gradient and providing further insight into the dynamics of the flow (Church *et al.* 1989; Smith *et al.* 1991).

Sealevel & ENSO relationships, and the rock lobster: 1986–88

The progression of the seasonal sea level cycle down the west coast and across the Great Australian Bight was linked with the Leeuwin Current by Pariwono *et al.*

(1986), who also suggested an association with *El Nino/* Southern Oscillation (ENSO) events. Pearce & Phillips (1988) in turn showed that annual settlement of the puerulus stage of the western rock lobster is highly correlated with the strength of the Leeuwin Current: during ENSO years, annual mean sea level is relatively low (implying a weak Leeuwin Current) and puerulus settlement is poor compared with *La Nina* periods.

Feng *et al.* (2003) have since quantified the association between sea level and the Leeuwin Current transport, and ENSO/Leeuwin Current links with other Western Australian commercial fisheries were subsequently shown by (*inter alia*) Lenanton *et al.* (1991) and Caputi *et al.* (1996).

Modelling studies: 1986 –

There have been corresponding advances in both theoretical and numerical modelling of the Leeuwin Current system. By including thermohaline forcing in a linear stratified model of the circulation in the southeastern Indian Ocean, McCreary *et al.* (1986) were able to reproduce the alongshore steric height gradient and eastward geostrophic flow presented by Godfrey & Ridgway (1985) and so force a poleward surface boundary current against the prevailing winds. The equatorward undercurrent was also represented.

Batteen & Rutherford (1990) developed the first numerical model with sufficient spatial and temporal resolution to depict the generation and general properties of the Leeuwin Current and the associated eddy field – the results agreed well with the 1986/87 LUCIE current meter observations. Domingues *et al.* (2007) subsequently used a particle tracking technique to reveal links between the various sources of the Leeuwin Current and the regional circulation.

The Leeuwin Current Symposium: 1991

A one-day symposium held in 1991, sponsored by the Royal Society of Western Australia with invited speakers addressing pre-selected topics, attempted to summarise the existing state of knowledge and understanding of the geology, physics, meteorology and biology of the Leeuwin Current. The set of 13 papers (Pearce & Walker 1991) included comparisons between the climates, oceanography and biology of the eastern boundary current systems in the southern Pacific, Atlantic and Indian Oceans (the Humboldt, Benguela and Leeuwin Currents respectively). There was also a focus on the role played by the Leeuwin Current on the fisheries, corals, seagrasses and seabirds along the Western Australian coast.

New satellite technologies (altimeter and ocean colour): 1990s –

The advent of operational satellite altimetry (primarily TOPEX/Poseidon from 1992) provided for the first time global surface ocean currents on a regular basis at eddy-resolving temporal and spatial scales (*e.g.*, Fang & Morrow 2003; Feng *et al.* 2005), leading to the ability to model larval transport processes (Griffin *et al.* 2001) and ultimately to web-based ocean currents charts and the Bluelink ocean forecasting website (http://www.bom.gov.au/oceanography/forecasts/).

Similarly, the launch of SeaWiFS in August 1997 provided for the first time direct remote sensing measurements of marine biological processes on an operational basis, yielding near-surface chlorophyll concentrations from satellite ocean colour observations (Moore *et al.* 2007). Clark & Li (2004) subsequently used satellite altimetry to show that the onshore geostrophic transport associated with the alongshore steric height gradient is enhanced during *La Nina* periods and may contribute to the observed inter-annual variability in puerulus settlement.

Focused multi-disciplinary research vessel surveys: 2000s

A series of multi-disciplinary cruises undertaken by the University of Western Australia and CSIRO on the FRVs *Franklin* and *Southern Surveyor* examined the dynamics of the Leeuwin Current and associated shelf circulation. Covering the southwestern and south coasts, complemented by repeated transects off Two Rocks during the Strategic Research Fund for the Marine Environment (SRFME – Keesing *et al.* 2006), these surveys described the seasonal water properties, circulation and some aspects of the biology along the continental shelf and in the Leeuwin Current. The dominant current systems and physical water properties along the coast have been summarised by Woo & Pattiaratchi (2008) and Pattiaratchi & Woo (2009). The seasonal biophysical characteristics of the Ningaloo and Capes regions were covered in detail by Hanson *et al.* (2005a, 2005b) and Woo *et al.* 2006, while the repeated SRFME transects clearly demonstrated how seasonal changes in the chlorophyll maximum layer are linked with the annual strengthening of the Leeuwin Current (Koslow *et al.* 2008).

The Leeuwin Current and its eddies: DSR Special Issue 2007

Details of the physical and biological structure of the Leeuwin Current and the offshore eddy field were described in a dedicated volume of Deep-Sea Research in 2007 ("The Leeuwin Current and its eddies": Waite *et al.* 2007). Results from research cruises were supplemented by a series of modelling papers to show the dynamic interactions between the Leeuwin Current, the Leeuwin Undercurrent and both warm-core and cool-core eddies, and the spatio-temporal variability of primary production along the shelf.

The Leeuwin Current 2007 Symposium

At this stage of the journey, we have been able to build on the advances made over the past few years and take a fresh look at the state of knowledge of the Leeuwin Current system, bringing together some of the recent research on the unique marine environment off Western Australia.

This special issue of the Journal of the Royal Society of Western Australia is complementary to the DSR 2007 volume by incorporating a series of reviews and some new results about the continental shelf oceanography and biology associated with the Leeuwin Current. The papers are published largely in the sequence in which they were presented at the Symposium. One orally-presented paper has been withdrawn, another has been split into two, and a third has been converted from a poster to a written paper. The first paper examines the evolution of, and long-term changes in, the "Leeuwin Current" over geological time-scales, suggesting that the southward flow (as we know it) was probably well established 2 to 3 million years ago (Wyrwoll *et al.* 2009), but recognising that indirect evidence of warmer waters in the geological past may not necessarily have been associated with a proto-Leeuwin Current *sensu stricto*. Fluctuations in the Leeuwin Current in response to plate reorganisation, tectonics and climate variability have resulted in major shifts in ocean temperature and sea levels along the Western Australian coast, with some of the responses to past changes providing possible guides to the response of the Leeuwin Current to anticipated future climate states.

This is followed by a series of papers reviewing the larger-scale oceanography from the source region(s) in the north, down the west coast and eastwards towards the Great Australian Bight.

The source waters of the Leeuwin Current in the far north are shown by D'Adamo *et al.* (2009) to originate from the tropical Pacific Ocean via the Indonesian Archipelago, together with a contribution from the northern Indian Ocean, both these sources being warm and relatively low in salinity. The Leeuwin Current itself assumes its identity as a strong poleward boundary current south of North West Cape. Some previously unpublished current meter measurements taken by MetOcean Engineers and the Australian Institute of Marine Science along the North West Shelf between 1995 and 2007 have been presented for the first time. The "Holloway Current" is the title proposed for the south-westward flow along the outer North West Shelf in honour of a deceased colleague who made major contributions to the oceanography of this region.

Two papers review the physical and biological oceanography along the west coast between Exmouth and Cape Leeuwin. The main current systems and accompanying water properties are addressed by Pattiaratchi & Woo (2009), defining the geography and seasonality of the Leeuwin Current (strongest in autumn/ winter), the Leeuwin Undercurrent (the northward current underlying the Leeuwin Current) and the wind-driven Capes and Ningaloo Currents which flow northwards along the inner continental shelf in summer. The authors define 8 water masses on the basis of their temperature/salinity/oxygen characteristics, with the Leeuwin Current itself largely being a combination of Tropical Surface Water and South Indian Central Water.

Feng *et al.* (2009) describe the seasonal and inter-annual variations in the strength of the Leeuwin Current and its associated offshore eddy field, these being stronger in winter than in summer and also in *La Nina* periods compared with *El Nino* years. By complementing satellite-derived chlorophyll-a data with shipboard measurements, biophysical mechanisms relating to variability of the ocean production off the west coast are examined. The important issue of the potential effect of long-term climate change on ocean production off the west coast is also addressed, with present evidence pointing to a probable reduction in the flow of the Leeuwin Current under more *El Nino*-like conditions in the future.

In a neat mix of oceanographic history, modern current measurements and numerical modelling, Cresswell & Domingues (2009) describe the seasonal influx of warm, low-salinity Leeuwin Current waters from the west coast around Cape Leeuwin and their subsequent penetration eastwards along the south coast of Western Australia. Westward of the Recherche Archipelago, current speeds of up to 1.8 m/s have been measured just off the shelf although they weaken further into the Great Australian Bight. Both cyclonic and anti-cyclonic eddies abound and (together with the winds) play a major role in the observed variability of the current system along the south coast.

Two papers on fish and fisheries off Western Australia complete the large-scale overviews.

Beckley *et al.* (2009) comprehensively review a variety of previous studies of larval fishes between the North West Shelf and the Great Australian Bight. Larval fish assemblages within the Leeuwin Current are found to be largely a mixture of oceanic, slope, tropical and temperate coastal species, with strong seasonal variability in species composition reflecting these different sources as well as seasonal changes in the strength and location of the Leeuwin Current.

Previously described relationships between the Leeuwin Current and recruitment to a variety of Western Australian commercial invertebrate and scalefish fisheries are re-examined by Lenanton *et al.* (2009). The close link between the strength of the Leeuwin Current and settlement of the puerulus phase of the western rock lobster has been confirmed, with some dependence on other factors such as water temperature and possibly ocean productivity (chlorophyll-a) and eddy kinetic energy. While environmental variables remain within historical ranges, the relationship between the Leeuwin Current and western rock lobster is likely to be maintained. Under these circumstances, and in the longer-term, weakening of the Leeuwin Current in response to an increasing frequency of *El Nino* events may result in lower puerulus settlements in future years. Most other fisheries (for example, scallops, whitebait and salmon) are essentially inshore-dwelling species which have exhibited varying responses to oceanographic factors such as the Leeuwin and Capes Currents, and coastal salinity, which is most likely a surrogate for some physical or biological factor that influences survival of larvae and newly settled juveniles.

A series of more regional studies dealing with aspects of the oceanography and biology of key areas follow: the Ningaloo reef system, the Houtman Abrolhos Islands, Rottnest Island, the Geographe Bay/Capes area and Esperance.

The unexpectedly high productivity of the Ningaloo Reef coastal area is attributed by Hanson & McKinnon (2009) to episodic regional upwelling driven by the seasonal north-flowing Ningaloo Current, enhancing nutrient concentrations along the inner shelf. During *El Nino* years in particular, primary production is greatly elevated but this is not necessarily reflected in copepod abundance; higher up the food chain, on the other hand, whale sharks are more abundant during *La Nina* periods with a strong Leeuwin Current than during *El Ninos*.

The biota at the Abrolhos Islands are addressed in a series of 3 papers dealing with the marine flora, fish and birds in the Island groups.

Phillips & Huisman (2009) compare the marine plants (both seagrasses and seaweeds) at the Islands with those along the mainland coast at Jurien Bay, finding that the offshore assemblage represents a mix of tropical and temperate species (reflecting the tropical origins of the Leeuwin Current) while at the adjacent mainland coast the species are almost all temperate – reminiscent of Saville-Kent's original observations in the late 19th century.

Fish species over the 100-km latitude range of the Abrolhos Islands (Watson & Harvey 2009) are dominantly tropical, with much lower proportions of warm-temperate and sub-tropical species. The species composition is intermediate between those observed at Ningaloo (22°S) and Rottnest Island (32°S). While on this larger spatial scale the distribution can be attributed to the Leeuwin Current, there is a high level of variation in the composition of fish assemblages within each location on a site to site basis. This small scale variability is likely a result of numerous factors, for example differences in habitat and food availability.

The Abrolhos Islands are a fertile breeding ground for seabirds such as the Lesser Noddy and Brown Noddy during spring and summer (Surman & Nicholson 2009). As their diet consists largely of larval fish, the Noddy breeding patterns and success reflect fluctuations in the abundance of fish which in turn appear to be linked to variations in the Leeuwin Current. During periods of weak Leeuwin Current (*El Nino* events), breeding is severely delayed and reproductive output is poor suggesting depleted prey fish abundance, while variations in other factors such as the nearshore current system and the offshore eddies may also have some influence on food availability. This long-term dataset may provide a valuable insight going forward into the changing dynamics of current systems and potential impacts upon seabirds along the Western Australian coast.

Further south, a detailed analysis of a year-long current meter mooring off Perth has yielded invaluable information of the temporal variability and vertical structure of the currents down the water column (Cresswell 2009). Winter current speeds peaked at 0.6 m/s (associated with the Leeuwin Current, although the main core of the flow was probably further offshore), while in summer the northward flow of the Capes Current was evident, with a maximum observed speed of 0.9 m/s. Wind played a dominant role in the direction of the currents, and there were considerable cross-shelf current excursions – with obvious implications for the cross-shelf transport of marine larvae.

Historical current measurements are analysed by Pearce & Hutchins (2009) to study seasonal and inter-annual variations in the recruitment of two tropical damselfish species into the shallow reefs at Rottnest Island. Based on the observed current speeds both on and off the shelf, the authors suggest that the higher southward speeds in the Leeuwin Current (rather than the weaker, reversing shelf current system) are required to transport pelagic larvae southwards from their spawning grounds at the Abrolhos Islands to Rottnest within their normal pelagic larval duration of about 3 weeks. Under favourable current conditions, larvae spawned at Shark Bay can reach Rottnest Island within the 3 week period.

Continuing southwards, the distributions of fish and algae in the Capes region (Westera *et al.* 2009) show relatively few fish species of tropical or subtropical origin. There is however a large component of fish species classified as subtropical-temperate (44%), in addition to the expected temperate species. These distributions, however, are not closely linked with water temperatures, and the authors conclude that the Capes region is part of a large biogeographical transition zone. Likewise, the bulk of marine algae are temperate, but southward and northward range extensions are attributed to the Leeuwin and Capes Currents.

The influence of the Leeuwin Current on the marine biota along the south coast (on both geological time-scales and in the present) shows a gradient in the relative proportions of subtropical, south-western endemic and southern temperate species from west to east (Kendrick *et al.* 2009). Examining the distribution of macroalgal assemblages in particular, the rich diversity and high local species turnover has been attributed largely (but not exclusively) to the Leeuwin Current.

A key feature of recent work on the Leeuwin Current system has been the interplay between the physics and the biology, with consequent benefits to our understanding of the dynamics of both. William Saville-Kent would have been interested to see how far we have come.

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